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14. ABSTRACT
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On the Mutual Information of Multi-hop Acoustic Sensors Network in Underwater Wireless Communication

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In the second part of the research, we work on experimental data received from a pair of SAM-1 acoustic sensors provided by Desert Star Systems. We use information theoretic tools of entropy, conditional entropy, probability mass function etc. of input and output data signal to analyze the mutual information, information loss, bit error rate, and channel capacity. The significant research of this thesis is observing the multi-hop relay network model and to analyze the optimal distance, frequency, and capacity for available bandwidth in Underwater Wireless Sensor Network (UWSN). Various algorithms are discussed emphasizing on non-coherent approaches. Noise in UWC is considered to be white Gaussian.

On the Mutual Information of Multi-hop Acoustic Sensors Network in Underwater Wireless Communication

By

Raju Kumar Shrestha

A thesis submitted to Graduate Faculty of the
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On the Mutual Information of Multi-hop Acoustic Sensor Networks in Underwater Wireless Communication

Raju Kumar Shrestha

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List of Notations

SNR	Signal to Noise Ratio
SNR_o	Signal to Noise Ratio of each node
d	Link distance
C	Channel Capacity
BW	Bandwidth
P	Power of Signal
N_o	Power of Noise
E_S	Signal Energy
E_N	Noise Energy
f	Carrier Frequency
c_s	Sound Speed
dB	Decibel
α	Absorption Coefficient
$\theta_b(k)$	Periodic Autocorrelation
A(r,f)	Path-loss in Underwater Communications Channels
$a(f)$	Absorption Coefficient
KHz	Kilo Hertz
MC	Monitoring center
$N_o(f)$	Noise in Underwater Communication Cannels
PSD	Power Spectral Density
P_b	Probability of Error
$S_r(f)$	Power Spectral Density of the Received Signal
$P_{e,N}$	BER of *N*-hop link
$P_{e,1}$	BER of each hop
R	Bit rate
b	scaling factor for bandwidth
c	scaling factor for capacity
p	scaling factor for power
N	Number of hops over a link distance

d_p	length of the p-th propagation path
s	shipping activity factor
$I(X;Y)$	Mutual information between X and Y
$H(X)$	Entropy of X
$H(Y\|X)$	Conditional entropy of Y given X
$p(x)$	Probability distribution of X
$p(x, y)$	Joint probability distribution of X and Y

List of Abbreviations

UWC	Underwater Wireless Communication
UAC	Underwater Acoustic Communication
BER	Bit Error Rate
UWSN	Underwater Wireless Sensor Network
SNR	Signal to Noise Ratio
SINR	Signal to Interference and Noise Ratio
BW	Bandwidth
BS	Base station
CH	Cluster Head
BPSK	Binary Phase Shift Keying
PPM	Pulse Position Modulation
PN	Pseudorandom Noise
CDMA	Code Division Multiple Access
log	Logarithm in base 10
$\log_2$	Logarithm in Base Two
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Spectrum
PSD	Power Spectral Density
TL	Transmission Loss
AWGN	Additive White Gaussian Noise
DPI	Data Processing Inequality
MAI	Multiple Access Interference

Summary

In this thesis, we investigated the performance of wireless sensors in cascaded multi-hop relay network in Underwater Acoustic Communication (UAC) to see the optimum data rate that can be transmitted through the channel with a minimum bit error rate. We explored the experimental evaluation and simulation result for the mutual information between transmitted signal and received signal in aquatic channel. We optimized the mutual information, finding optimum channel capacity for a cascaded multi-hop channel network. Our results revealed that the placement of multiple sensor nodes over a long range in underwater communication improves the channel capacity in a significant way. A relay system network with multiple sensor nodes at different distances reduced the propagation loss, information loss, multipath fading etc. and minimizes the bit error rate (BER).

Since UWC is bandwidth limited, we studied the relationship of capacity with transmission power, bandwidth and carrier frequency. In comparison with the free space wireless communication, the underwater acoustic communication suffered from the limits of the less available bandwidth, multipath effect, and the complex noise caused by the underwater acoustic channel. Therefore, we explored a relay-aided UAC in order to enhance reliability in long distance underwater communication and defy the challenging problems such as frequency dependent signal attenuation, long propagation delay, and information loss. The result illustrated better performance in terms of improvement in channel capacity, minimum BER, and the increase in mutual information compared to traditional direct link UAC. In addition, effects of various system parameters on channel capacity were considered such as source to destination distance, transmit power allocation, sensor node location, carrier frequency etc. To demonstrate the merits of above discussed network model, we simulated its BER performance. Comparison was made with traditional direct link systems to reveal the communication reliability of new network model.

We focused on channel capacity as a function of SNR for different link distances. Our contribution on maximization of mutual information between transmitted information and received information was done by determining the optimal carrier frequency and node distance. Thus, optimal frequency was derived in terms of transmission distance and power allocation. Our findings proved that the optimal frequency decreases with an increase in range. Similarly,

capacity of the relay channel increased with an increase in the number of hops for varying link distances.

Chapter 1

Introduction

In this thesis, we investigate the performance of acoustic sensor networks in underwater wireless communication in terms of mutual information, channel capacity, bit error rate, and information loss based on the transmission power, distance, carrier frequency and the bandwidth of the channel. A placement of multiple acoustic sensors in a multi-hop relay form is needed in numerous applications where data transmission has to be accomplished beyond short distances. This network is effective since the bandwidth of an underwater acoustic communication is severely limited and decays with increase in distances. It is advantageous to accomplish such transmission using sensors in a multi-hop relay form keeping constraints such as transmission rate, transmission delay, Signal-to-Interference and Noise Ratio (SINR) under consideration. In particular, we consider a communication scenario where a certain number of bits have to be transmitted over a distance d. Our result analyzes the optimal number of sensor nodes, N to use over a link distance d to increase the mutual information between transmitted data and received data in terms of link capacity, delay, information loss, and bit error rate.

This work is supported by the grant titled, "Information – Driven Doppler Shift Estimation and Compensation Methods for Underwater Wireless Sensor Networks," (Department of Defense Research Grant W911NE-11-1-0144) which considers fundamental research problems [11]. The proposal centralizes innovative information driven approaches to make a decision for sensor collaboration related to the network information constraints.

Different goals of the above mentioned project can be summarized as [11]:

1) To analyze and improve the non-data aided methods for Doppler shift estimation and compensation (squaring time phase recovery method, power spectrum method, and partial autocorrelation method);
2) To determine the necessary quantity and deployment strategy of sensors in a given region, and to provide a required security level;
3) To minimize the probability of false alarm and the bit error rate;

4) To improve decision-making on target detection with sensor collaboration in the context of blind Doppler shift estimation and detection, and

5) To improve the ability of a distributed sensor system to detect intruders (targets) and determine how the network wireless sensor design is affected.

Our thesis concentrates on improving mutual information between two data signals in terms of minimum bit error rate, maximum data rate communication, and channel performance. We focus on sensor placement in multi-hop to minimize the bandwidth consumption and mitigate the risk of acoustic link failure and information loss. In order to reduce the communication load for each sensor we develop new distributed algorithms for underwater communication similar to those developed in wireless communication in [14]. The advantage of this sensor placement will help in fulfilling the increasing demand for reliable maximum data rate wireless communication links to accommodate the wide range of underwater application. We also define algorithms that reduce the significant challenges to the development of underwater wireless systems such as complex channel noise, bandwidth limitations, and frequency and distance dependent signal attenuation [5].

According to Shannon (1948), the mathematical theory of channel capacity is based on the notion of maximizing the mutual information between the input and the output of a system. The growing demand for underwater wireless communication gives great importance to determining capacity limits of acoustic channels for different network models. These capacity limits show the maximum data rates that can be transmitted over wireless channel with small error probability. Shannon defines channel capacity as the channel's mutual information maximized over the all the possible input distributions. UWC impose many constraints that affect the design of wireless network such as path loss, transmission distance, and energy absorption by water, long propagation delays, channel dispersion, Doppler shift, and interference. However, after the wide development in wireless digital communications for the underwater environment, it is important to improve the mutual information, data rate, channel capacity, information loss, probability of error etc. of existing systems. In our thesis, we modeled our sensors as a multi-hop relay network to maximize mutual information for point to point Gaussian channels between transmitter and receiver in the underwater environment.

Our contribution is on UWSN design for long range acoustic communication placing an optimum number of sensor nodes at an optimum distance for certain average transmission power. A simple mathematical model assessing the dependence of an acoustic communication channel capacity on the distance is given in [3], where the acoustic path loss experienced by a signal of frequency f propagating in a horizontal distance d was modeled as $A(d, f) \sim d^k a(f)^d$, where k is the spreading factor and $a(f)$ the absorption coefficient. The capacity calculation is accompanied with two types of bandwidth, i.e. a 3 dB design principle and an optimal capacity-maximizing principle.

Similarly, maximizing the mutual information with an upper bounded average power yields the same channel capacity [6]. The algorithm in [6] focuses on relationship between power, transmission band, distance and capacity for the Gaussian noise scenario in a closed form. This model estimates for power consumption, band edge frequency and bandwidth as functions of distance and capacity required for a data link. This approximate model stems from an information theoretic analysis that takes into account a physical model of acoustic propagation loss and both physical and ambient noise. It shows that the power and band of operation can be adjusted to maximize mutual information to a certain capacity level.

Both carrier frequency and bandwidth selection are important in UWSN design for multi-hop relay networks. For long range communication, frequency has to be lowered and the available bandwidth to work will be just few kHz. We focus on non-coherent channels for maximizing the mutual information between transmitter and receiver. We study the transmission distance, data rate, and channel noise to get the maximum of the digital information embedded in the received signal to maximize the mutual information.

In this thesis, we applied a multi-hop relay sensor node by dividing the total link into multiple hops, where a relay acoustic node is employed at each hop. The relay node receives the signal, regenerates it, and passes it on to the next hop, until the final destination is reached. The question of interest to our design is how exactly does this approach gives improvement in terms of maximizing the mutual information, total power consumed, energy per bit, overall cost and delay. We use an information theoretic tool to accomplish the assumption that the capacity of relay channel is equal to the capacity of each of its hops, and are shown to increase with the number of relays. Here, we show that relaying also helps to reduce the total transmission power

and its benefits are even more pronounced in view of energy per bit savings. We consider system optimization in the light of minimizing both bit error rate and the information loss.

Multi-hop relay acoustic sensor network channels are useful in system design in which transmission rate is optimized according to the number of hops. The result makes use of a basic acoustic path loss model, thus providing guideline for the design of a general relay acoustic link. We calculate the optimal carrier frequency and input signal PSD to maximize mutual information and improve channel capacity.

1.1. Thesis Structure

To understand the underwater acoustic communication, its channel capacity, information loss, and signal power allocation; one requires knowledge of information theoretic tools, digital communication, and signal processing. Also, we have extensively used the Matlab programming in system design and simulation of sensors placement to maximize the data rate, mutual information, and channel capacity. It is also very important to explain a few details in appreciable the thesis.

The rest of the thesis is structured is structured as follows:

Chapter 2 introduces our sensors network model for sensors placement in multi-hop relay form.

Chapter 3 provides the detail about the optimal frequency and distance for underwater communication along with the bit error rate and delay that incurs due to multi-hop relay network.

Chapter 4 explains the proposed model of multi-hop relay network in underwater communication valid from Information theoretic point of view too. It also briefly discusses entropy, joint Entropy, information loss, and mutual Information.

Chapter 5 discusses about the modulation techniques for the scenario of multi-hop relay network in underwater wireless communication.

Chapter 6 does the simulation and analytical study for optimal distance, frequency, transmitted power as a function of number of hops in an Underwater Acoustic Channel.

Chapter 7 contains the main observation and results from experiment performed at swimming pool. We studied the mutual information and information loss from the observation of bit error rate due to channel noise, distance, and carrier frequency in underwater acoustic communication.

Chapter 8 provides the conclusion and scope for future work.

1.2 Thesis Significance, Contribution and Findings

This main scope of thesis is to maximize the mutual information between transmitter and receiver in long range communication in an underwater channel for high data rate transmission using a multi-hop relay network. It focuses on the mathematical algorithm for long range horizontal acoustic communication for optimal frequency, power allocation, distance and available bandwidth. We use direct sequence spread spectrum (DSSS) and PN-sequence modulation as better methods of modulation that is robust to noise and interference.

This research contributes to Dr. Cotae's UDC research titled "Information - Driven Doppler Shift Estimation and Compensation Methods for Underwater Wireless Sensor Networks" (Research Grant W911NE-11-1-0144), which is to analyze and develop non-coherent communication methods at the physical layer for target tracking and use the information theory tools to predict the next target position by processing the data information collected from a collaborative wireless distributed sensor network.

Chapter 2

Underwater Acoustic Communication Channel

In this chapter, we provide a background review on concepts used throughout the thesis. We review path-loss, effect of noise and interference, propagation delay, and long range acoustic communications. We review information theoretic tool terminologies such as mutual information, entropy, joint entropy, conditional entropy, and channel capacity.

2.1 Underwater Channel Model

An underwater communication channel is very complex and communicates through propagation of sound, called acoustic communication. Underwater acoustic sensor networks are then formed by acoustically connected bottom sensor nodes, autonomous underwater vehicles, and surface stations that serve as gateways and provide radio communications link to on-shore stations. Underwater acoustic sensor networks consist of sensor nodes and vehicles deployed underwater and networked via the acoustic links to perform collaborative monitoring tasks. However, acoustic channels impose many constraints that affect the design of UWC systems. These are characterized by path loss that depends on both the transmission distance and the signal frequency. The signal frequency determines the absorption loss, which increases the distance as well, eventually imposing a limit on the available bandwidth.

Table 1. Underwater Acoustic Communication System Ranges [3]

Distance	Range(Km)	Bandwidth (KHz)
Short	0.1	>100
Very short	0.1-1	20-60
Medium	1-15	10
Long	15-100	2-6
Very long	1000	<1

Table I shows typical bandwidth of the underwater channel for different ranges. The table is generated using 3dB bandwidth module for relation between relative SNR and frequency from Figure 11. This shows that long-range systems that operate over kilometers may have a bandwidth of only a few kHz, while a short-range system operating over few meters may have more than a hundred kHz bandwidth. This is true because carrier frequency is higher for short range acoustic communication which will give a wide bandwidth to transmit the signal. Likewise, for long range acoustic communication, carrier frequency is lowered and available bandwidth is small.

2.1.1 Acoustic Transmission Loss

Acoustic path loss depends on both signal frequency and distance. The dependence is a consequence of absorption, i.e. acoustic energy is transferred into heat energy during sound propagation from one point to another.

$$A(d,f) = d^{\alpha} a(f)^{d} \tag{2.1.1}$$

where d = total transmission distance (km)

f = carrier frequency (kHz)

$a(f)$ = absorption coefficient (dB/km)

α = spreading factor

In addition, signal experiences a spreading loss which also increases with distance. Spreading loss refers to the energy distributed over an increasingly larger area due to the regular weakening of a sound signal as it spreads outwards from the source. The overall transmission loss that occurs in UW channel over a transmission distance at a signal frequency *f* is given by [3]:

$$TL = \alpha\ 10 \log d + d\ 10\ \log a(f) \tag{2.1.2}$$

where α is spreading factor (α *=2* for spherical spreading, α *=1* for cylindrical spreading, and α *= 1.5* for the practical spreading), *d* is transmission distance in meters. In general, for shallow water channels, cylindrical spreading is assumed (α =1) while for deep water channels spherical

channels is assumed (α =2). And $10\ \log a(f)$ is the absorption coefficient expressed using the Thorp's formula, which gives $a(f)$ in dB/km for f in kHz as follows [3]:

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f} + (2.75)10^{-4} f^2 + 0.003 \tag{2.1.3}$$

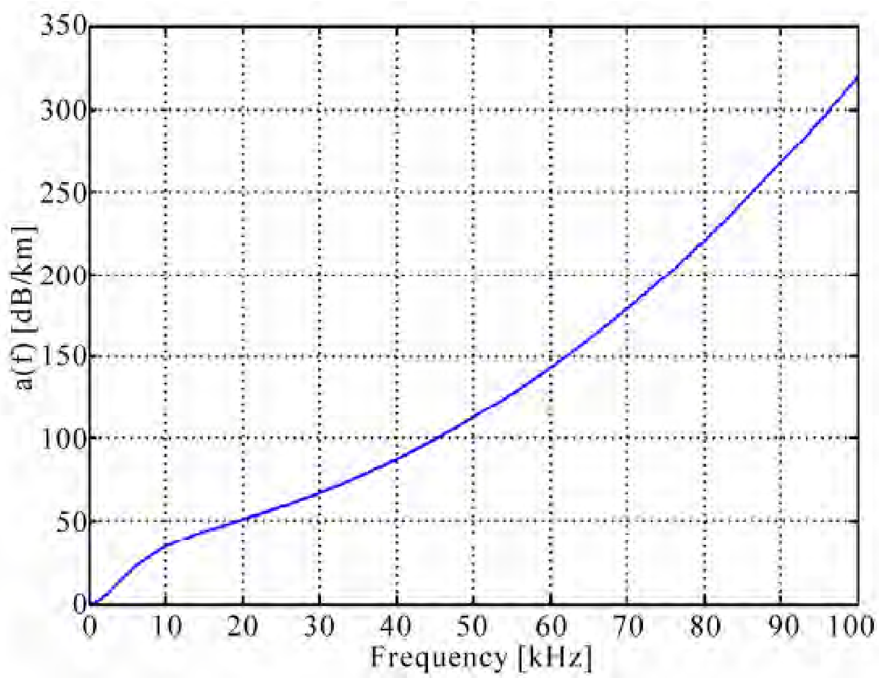

Figure 1 Absorption coefficient vs. frequency

2.1.2 Noise

Noise in an underwater channel affects communication system by altering signal strength and reducing channel capacity. The noise in acoustic channel constitutes of four different sources: turbulence, shipping, waves, and thermal noise. Turbulence noise influences on very low frequency region, $f \leq 10$ Hz. Noise caused by distant shipping is dominant in the frequency region 10 Hz -100 Hz, and it is modeled through the shipping activity factor s, whose value ranges between 0 and 1 (for low and high activity). Surface motion, caused by wind-driven waves (w is the wind speed in m/s) is the major factor contributing to the noise in the frequency region 10 Hz -100 kHz (which is the operating region used by the majority of acoustic systems). Finally, thermal noise becomes dominant for $f \geq 100$ kHz [2].

The noise in an acoustic underwater channel under discussion is complex additive colored (frequency dependent) Gaussian noise with zero mean and power spectral density (PSD) $N_o(f)$ that decays linearly on the logarithmic scale in the frequency region 1–20 kHz. We use the same approximation as given in [2] for the PSD of noise in an acoustic channel

$$10 \log N_o\left(f\right) = N_1 - \eta \log\left(f\right) \tag{2.1.3}$$

for the positive constant $N_1 = 50$ dB re μ pa [24] and $\eta = 18$ dB/decade [21]. Obviously, the noise PSD of a narrowband underwater network depends on the carrier frequency but it is flat over the communication band. Hence, the noise effect in underwater wireless communication is carrier frequency dependent.

2.1.3 Channel Capacity and Signal-to-Noise Ratio

The channel capacity strictly depends in transmission distance, carrier frequency, and bandwidth in an underwater acoustic communication. The channel is time variant and the ambient noise is assumed to be Gaussian. Channel capacity is the information rate over the acoustic link which is bounded by the Shannon capacity defined as:

$$C = (BW) \log_2(1 + SNR) \tag{2.1.4}$$

where BW is bandwidth of the system in kHz and SNR indicates the signal to noise ratio.

$$C = BW\ log_2\left(1 + \frac{P}{N}\right) \tag{2.1.5}$$

where P = Power of signal (Watts or Volts^2)

N = Power of noise (Watts or Volts^2)

It can be seen from equation 2.1.5 that, for a source with constant power and limited bandwidth, the capacity of a channel is highly dependent on the noise power. Since, noise and attenuation is a function of distance and frequency, using $A(d, f)$ and PSD $N_o(f)$, the signal-to-noise ratio (SNR) at receiver, at distance *d* and frequency *f* for a transmitted power of *P* is given by [6]:

$$SNR = \frac{P}{BW\ A(d, f) N_o(f)} \tag{2.1.6}$$

Combining equation 2.1.4 and 2.1.6, we get the channel capacity for an acoustic link for optimal link distance and frequency as below [6]:

$$C = (BW)\log_2(1 + SNR) = (BW)\log_2\left(1 + \frac{P}{(BW)A(d,f)N_o(f)}\right) \qquad (2.1.7)$$

2.2 Network model: Multi-hop relay sensor network

The multi-hop relay networks have been extensively studied in terrestrial environments to provide reliable communications with extended transmission distance. However, due to peculiar characteristics of the UAC channel, the benefits of multiple sensor nodes in UAC needs to be re-evaluated, and requires special design and modulation. In our research, a multi-hop relay setup is considered; where all relays locate on line and are equally spaced with same transmit power. We investigate the maximum data rate transmission and mutual information for a relay node through analytical and numerical results. Accordingly, we compare performance of channel capacity with the traditional direct link system, and affecting factors of the system capacity like power allocation, link distance, available bandwidth, information loss, and bit error rate (BER).

First we discover an end to end direct link systems BER, and information loss corresponding to an optimum carrier frequency and signal bandwidth. Later, same observation is performed for multi-hop relay network and mutual information gain in UAC is evaluated. The affecting factors of channel performance are studied, which includes the data rate, distance from source to destination, and carrier frequency. We optimize the system for performance evaluation with respect to maximum mutual information and channel capacity for desired low BER and minimum information loss.

We consider a relay link as shown in Figure 1. The total link distance *d* is divided into *N* multi-hops, such that the length of each hop is *d/N*. The link is designed so that the signal-to-noise ratio at the input to each relay equals the target value SNR_o. This design ensures a fair comparison between a multi hop and a single-hop link. In what follows, we shall use the capacity in the optimal sense, i.e. the bandwidth and the power is defined as those that maximize the channel capacity under the constraint of fixed total power needed to ensure the desired SNR. With each type of bandwidth selection, there is an associated transmission power required to

achieve pre-specified SNR at the receiver. In particular, it is shown in [6] that for a given required SNR, the following relationships hold:

$$B(x) = B_o(d/d_o)^{-\beta} = bd^{-\beta}$$

$$C(x) = C_o(d/d_o)^{-\gamma} = cd^{-\gamma}$$

$$P(x) = P_o(d/d_o)^{\varphi} = pd^{\varphi} \quad (2.2.1)$$

Each of these quantities is thus characterized by two model parameters: the scaling factor b for bandwidth, c for capacity, p for power and exponent β, γ, φ respectively.

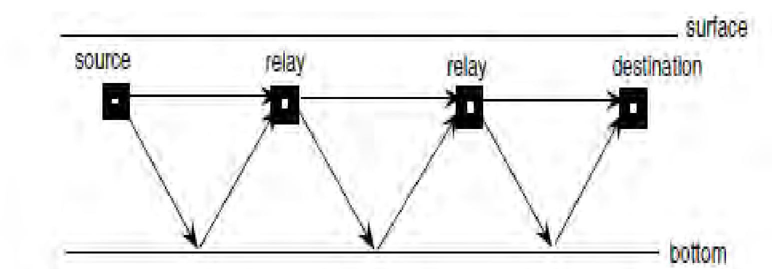

Figure 2 Illustration of Multihop network.

2.3 Conclusion

In this chapter, underwater acoustic communication channel model and parameters are reviewed. We discuss the dependency of link distance and carrier frequency in attenuation and ambient noise. Similarly, our network model and approached acoustic sensors network topology and parameters relating to UWSN are explained.

Chapter 3

Communications Channel and Algorithm

In this chapter, we mathematically define and derive the algorithm for multi-hop relay communications channels where we analyze an optimum placement of sensor in long range of communication link. We studied an algorithm that will optimize the BER and information loss for given link distance and proposed relay network.

3.1 System Optimization

Using an expressions (2.2.1) for N multi-hops and transmission link distance d, the channel capacity of each hop is determined as $C(d/N)$ in terms of bits per second, and the capacity of each node link is equal to [7]:

$$C_N(d) = C(d/N) \tag{3.1.1}$$

A similar relationship can be established for the bandwidth,

$$B_N(d) = B(d/N) \tag{3.1.2}$$

where $B(d/N)$ is the bandwidth of each hop measured in kHz.

The bandwidth efficiency, defined as $C_N(d)/B_N(d)$, follows a reverse trend which means it decreases as the hop distance becomes shorter. However, the absolute value of the bandwidth efficiency does not change much for the range of values d and number of hops N**.**

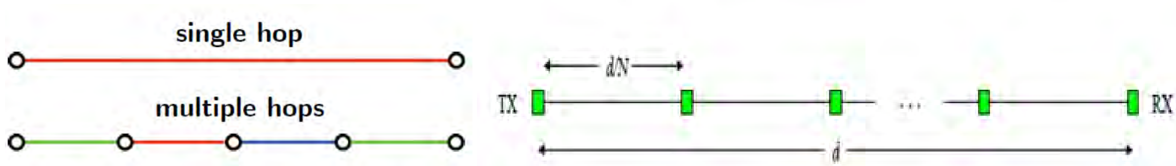

Figure 3 Non-cooperative linear multi-hop relay

Similarly, the power needed to transmit over a one hop is equal to $P(d/N)$ measured in Watts or Volts^2, and the power needed to span the entire link is:

$$P_N(d) = NP(d/N) \tag{3.1.3}$$

$$P_t\left(\frac{l}{N}\right) = 2\pi H \times 10^{1.9\log(l/N)+\frac{3.971(l/N)}{l/N+361}+0.0002(l/N)+0.1SNR_0+6.095} \times 0.67 \times 10^{-18} \qquad (3.1.4)$$

$SNR_0 =$ *SNR* at transmitter node

$H =$ Water depth

$$P(l) = SNR\,(l,f)A(l,f)N(f)(BW) \qquad (3.1.5)$$

As it can be expected, less power is required with deployment of numerous nodes or using sensor relays. While such situation is typical of any wireless channel, the heavy dependence of the capacity on the number of relays is particular to the UAC. This fact bears influence on the energy per bit needed to transmit over the distance *d*. If the transmission is accomplished over *N* hops, the energy per bit is:

$$E_N(d) = \frac{P_N(d)}{C_N(d)} = \frac{NP_N(d)}{C_N(d)} \qquad (3.1.6)$$

The equation above shows that how the energy per bit $E_N(d)$ decreases with number of hops. The benefits of multi-hopping are most evident in this metric, as it combines the power reduction and the capacity (bandwidth) increase simultaneously as the given link is divided into more hops.

After this, optimum operating frequency is selected from algorithm such that there is minimum path loss and BER is minimal. The signal-to-noise ratio, $SNR(d,f)$ which is equivalent to maximizing the channel capacity, leads to the maximization of $S_d(f)$. From chapter 2, equation 2.1.7,

$$SNR(d,f) = \frac{S_d(f)}{A(d,f)N_o(f)} = \frac{P}{(BW)A(d,f)N_o(f)} \qquad (3.1.7)$$

where $S_d(f)$ is the power spectral density of received signal in Watts per Hertz.

Given the required rate for the link R, the bandwidth BW and the frequency f we obtain $A(d,f)$ as:

$$A(d,f) = \frac{P}{(BW)N_o(f)(2^{R/_{BW}} - 1)} \tag{3.1.8}$$

3.2. Bit Error rate Simulation

Bit error rate performance of a receiver is a figure of merit that allows different designs to be compared in a fair manner. The first step to analyze the mutual information and capacity of system is to find BER. Using the bit-error probability and Shannon's communication theory, the upper bound of mutual information is obtained both analytically and in simulations.

Bit error rate testing with Matlab is very simple, but does require some prerequisite knowledge. BER testing requires a transmitter, a receiver, and a channel. We begin by generating a long sequence of random bits, provide as input to the transmitter. The transmitter modulates these bits onto some form of digital signaling, which we send through a simulated channel. We simulate the channel by adding a controlled amount of noise to the transmitted signal. This noisy signal then becomes the input to the receiver. The receiver demodulates the signal, producing a sequence of recovered bits. Finally, we compare the received bits to the transmitted bits, and tally up the errors. BER performance is usually depicted on a two dimensional graph. The ordinate is the normalized signal-to-noise ratio (SNR) expressed as $E_b\,/N_0$: the energy-per-bit divided by the one-sided power spectral density of the noise, expressed in decibels (dB). The abscissa is the BER, a dimensionless quantity, usually expressed in powers of ten. The achievable data throughputs, and the reliability of an underwater acoustic communication system, as measured by the BER, must be determined to suit the bandwidth limitations and distortions of underwater acoustic channels. The BER tolerance of about 10^{-2} makes it a viable model for poor quality band-limited underwater channels.

Due to filtering and other delay-inducing operations, for typical of most receivers, there is an offset between the received bits and the transmitted bits. Before we can compare the two bit sequences to check for errors, we must first determine this off-set. One way to do this is by correlating the two sequences, then searching for the correlation peak. Suppose our transmitted bits are stored in vector T_X, and our received bits are stored in vector R_X. The received vector should contain more bits than the transmitted vector, since the receiver will produce meaningless outputs while the filters are filling and flushing. If the length of the transmitted bit vector is L_{Tx}

and the length of the received bit vector is L_{Rx}, the range of possible offset is between zero and $L_{Rx} - L_{Tx} - 1$. We can find the offset by performing a partial cross-correlation between the two vectors.

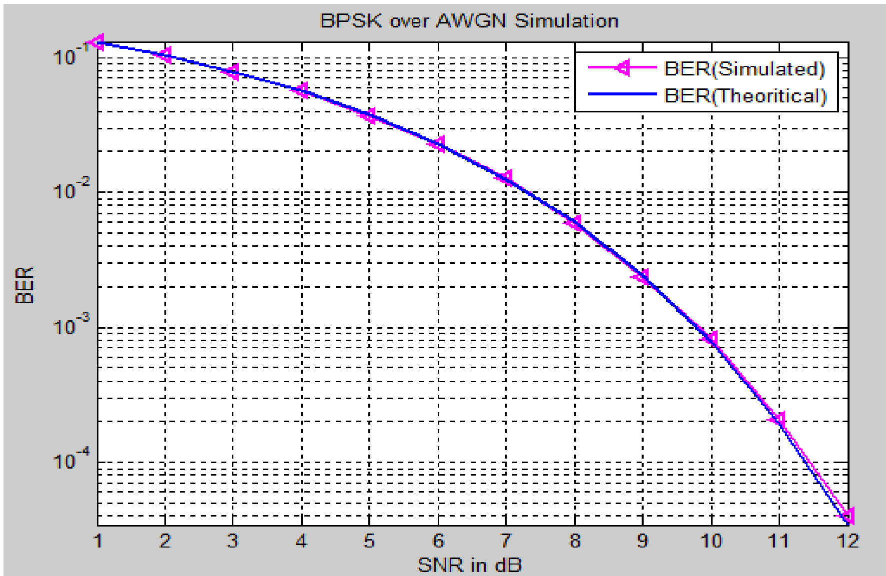

Figure 4. BPSK Simulation for BER v/s SNR of AWGN

The resulting vector is a partial cross-correlation of the transmitted and received bits, over the possible range of lags: 0: $L_{Rx} - L_{Tx} - 1$. We find the location of maximum value of correlation which tells us the offset between the bit vectors. Since Matlab numbers array elements as 1: N instead of as 0: $N-1$, we need to subtract one from the index of the correlation peak.

Once we know the offset between the transmitted and received bit vectors, we are ready to calculate the bit errors. For bit values of 0 and 1, a simple difference reveals bit errors. Wherever there is a bit error, the difference between the bits will be ± 1, and wherever there is not a bit error, the difference will be zero. Using Matlab, we calculate the error vector from the transmitted bit vector, T_X, and the received bit vector, R_X, along with the offset.

The error vector contains non-zero elements in the locations where there were bit errors. We need to tally the number of non-zero elements, since this is the total number of bit errors in our simulation. Therefore, we calculate the total number of bit errors, T_E, from the error vector.

Each time we run a bit-error-rate simulation; we transmit and receive a fixed number of bits. We determine how many of the received bits are in error, and then compute the bit-error-rate as the number of bit errors divided by the total number of bits in the transmitted signal.

3.3 Delay in multi-hop network

Delay in UWC is defined in terms of transmission delay and propagation delay. Delay is viewed as yet another form of cost associated with multi-hop sensor node network. The total transmission delay is important metric in the design of sensors network model for a long transmission distance. In digital communication system, it is beneficial that relays regenerate a packet, rather than simply amplifying and forwarding it. This way, noise accumulation along the link is prevented, and the performance, as measured by the overall BER stays close to that of single hop link with the same SNR. In particular, the BER of an N –hop link is given by the first order approximation [7]:

$$P_{e,N}(SNR_o) = 1 - (1 - P_{e,1}(SNR_o))^N \approx NP_{e,1}(SNR_o) \qquad (3.3.1)$$

where SNR_o is the input signal-to-noise ratio to each relay, and $P_{e,1}$ is the BER of each hop.

The approximation normally holds, since the link is designed such that $P_{e,N}(SNR_o) << 1$. Hence, the overall BER $P_{e,N}$ is only scaled, which is a minor degradation for a practical number of hops. However, the process of regeneration requires that the entire packet be received before it is passed on the next node, which introduces a delay. We focus for simplicity on the basic delay that occurs due to regeneration, not taking into account the time spent in repeated transmissions.

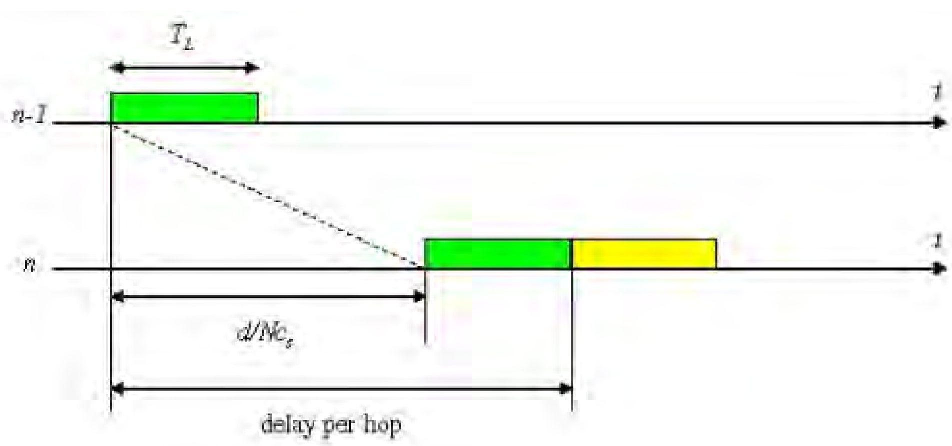

Figure 5. Delay between Relays

In Figure 4, the delay incur in regenerating a packet at the n^th relay node is illustrated. If a packet contains L number of bits (binary modulation can be assumed without loss of generality), then its duration is:

$$T_L = L/R \tag{3.3.2}$$

where T_L is duration in seconds and R is a bit rate measured in bits per second..

Assume a total link distance d is divided equally into *N* nodes. Then the propagation delay between each node will be:

$$P_d = d/Nc_s \tag{3.3.3}$$

where P_d = propagation delay between each node (seconds)

c_s = speed of sound in an underwater (normally 1500 m/s).

Packet regeneration introduces an additional delay equal to the packet duration T_L. Hence, delay per hop is the packet duration plus propagation delay, and the total delay that packet experiences over *N* hop is [7]:

$$D_N(d) = N\left[\frac{d}{Nc_s} + \frac{L}{R}\right] = \frac{d}{c_s} + \frac{L}{R}N \tag{3.3.4}$$

Therefore, the overall delay increases with *N*, and this fact imposes a limit on number of relays. We can assess the effect of number of relays into two cases. First, transmitter rate can be fixed regardless of the number of hops where delay will be linearly proportional to the number of nodes. Second, the transmission rate is allowed to vary with the node distance, so that it can be optimized according to the link capacity. In this case, the total delay is no longer a simple linear function of number of nodes. Instead, it depends on the number of nodes through transmission rate *R*.

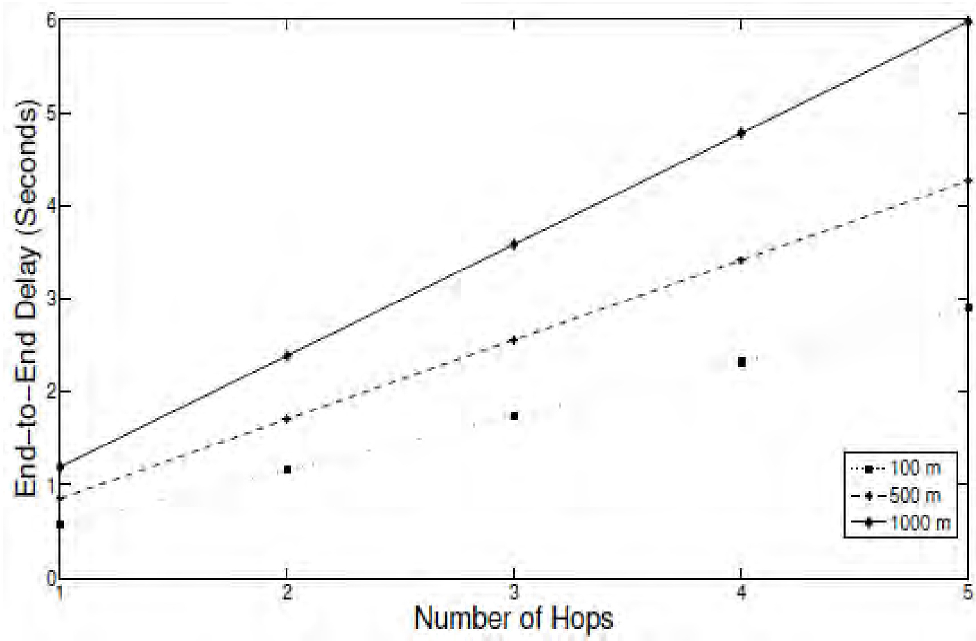

Figure 6 End-to-end delay of multi-hops relay network

In a practical system, transmission rate is proportional to available link bandwidth, which depends on the distance between nodes. Ideally, from information theoretic point of view, error free transmission can be accomplished at the rate equal to channel capacity. In either case, available transmission rate becomes a function of number of hops *N*. By increasing the number of hops, more packets contribute to overall delay by their duration T_L. However, each packet duration becomes shorter that accomplishes transmission faster over a shorter hop.

3.4 Conclusion

In this chapter, some insight for system optimization is discussed. Optimum distance and frequency, bit error rate and delay for transmission of large number of bits is also presented and discussed.

Chapter 4

Information Theoretic Analysis in Maximizing Channel Capacity

In this chapter, we go through maximizing mutual information and channel capacity analysis from information theoretic point of view. The basic performance measure is channel capacity that determines the maximum data rate that can be supported with an arbitrarily small error probability.

4.1 Mutual Information and Channel capacity

According to Shannon (1948), channel capacity is defined as channel's mutual information maximized over all the possible input distribution. Channel capacity is an upper bound of the mutual information that gives the maximum data transmission rate that can be reliably transmitted through a communications channel. The information channel capacity of a discrete memoryless channel is [20]:

$$C = max_{p(x)}\, I(X;Y) \qquad (4.1.1)$$

This quantity is defined as the maximum of the average mutual information *I*(*X*; *Y*) between input information *X* and its corresponding output information *Y* of the channel over a choice of distribution of *X*. Mutual information satisfies $I(X;\ Y\ ) =\ I(Y\ ;X) \geq 0$.

Considering *X* as the input and *Y* as the discrete output/detected output of the system, the mutual information is given by [9]:

$$I(X;Y) = H(Y) - H(Y|X) \qquad (4.1.2)$$

Entropy is also called self-information because $I(X;X) = H(X)$.

In other way, the mutual information *I(X; Y)* is the relative entropy between the joint distribution and the product distribution [20].

$$I(X;Y) = \sum_x \sum_y p(x,y) \log \frac{p(x,y)}{p(x)p(y)} \qquad (4.1.5)$$

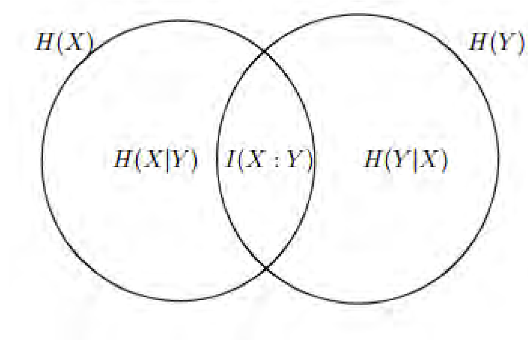

Figure 7. Graphical representation of Conditional Entropy and Mutual Information of X and Y

4.2 Markov Chain and Data Processing Inequality

We use the data processing inequality to show that information loss can be reduced forming the sensor nodes as a Markov chain. For data transmitted through $X \rightarrow Y \rightarrow Z$, the conditional distribution of Z depends only on Y and is conditionally independent of X. Specifically the joint probability function of for X, Y and Z can be written as:

$$p(x, y, z) = p(x)p(y|x)p(z|y) \tag{4.2.1}$$

We use above mentioned theory to maximize mutual information between random variable X and Z by deploying another sensor node Y in between the propagating distance of X and Z. This way, sensor node Y becomes a hop in-between transmission distance X and Z. Doing so reduces transmission distance, increases bandwidth, and data rate. In similar way, creating N nodes channels to transmit data from one point to another affected BER, information loss, mutual information, and channel capacity of the system.

Each sensor nodes in the network is made a primary transmitter with its own probability distribution and bit-error probability p. The objective of our thesis is to organize the sensors in a relay network system to optimize the transmitting signal power along long distance in an underwater communication.

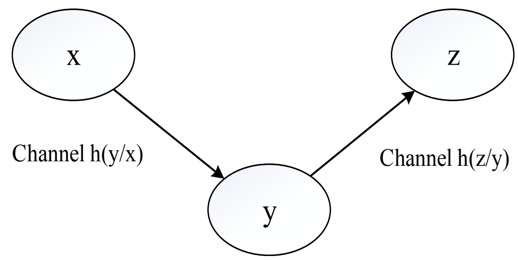

Figure 8. Cascaded Channel (Multi-hop) sensor network model

In this sensors network model, we re-transmit the received signal to another sensor node exactly as they are received. Thus, in order to obtain the input-output statistics of the cascade, we need only to consider the signal as one sample at a time. Let the information X of the first transmitter has its corresponding probability $p(x)$. The information X will transmit down the first channel and will be received as Y_1 by the first receiver sensor node, Y_2 by the second receiver sensor node, and finally as Y_i by the last receiver sensor node. During the observation of downstream transmission of information data from X to Y_i, each channel will have different conditional probability distribution since the channel state is changing with time i.e. for the i^{th} channel $p(y_i|y_{i-1})$ gives the probability distribution of the samples Y_i.

The channel capacity for discrete time Gaussian channel with signal power *'P'* for bandwidth limited performance is given by [21],

$$C = BW \ \log_2\left(1 + \frac{P}{BW\ N_o}\right) \tag{4.2.3}$$

However, by cascading and using data processing inequality [20] we have, for $X \to Y \to U \to V$,

$$I(X;V) \leq I(U;V) \tag{4.2.5}$$

We can find the $max\ _{p(x)}$of both sides,

$$C' = max_{p(x)}\ I(X;V) \leq C'' = max_{p(x)}\ I(U;V) = C(p_{(x)}) \tag{4.2.6}$$

Finding capacity of the product channel of the Markov chain [4], we obtain:

$$Y_1 \to X_1 \to X_2 \to Y_2$$

$$\begin{aligned}
I(X_1, X_2; Y_1, Y_2) &= H(Y_1, Y_2) - H(Y_1, Y_2|X_1, X_2) \\
&= H(Y_1, Y_2) - H(Y_1|X_1, X_2) - H(Y_2|X_1, X_2) \\
&= H(Y_1, Y_2) - H(Y_1|X_1) - H(Y_2|X_2) \\
&\leq H(Y_1) + H(Y_2) - H(Y_1|X_1) - H(Y_2|X_2)
\end{aligned}$$

$$I(X_1, X_2; Y_1, Y_2) = I(X_1; Y_1) + I(X_2; Y_2)$$

Therefore,

$$C = max_{p(x1,x2)} I(X_1, X_2; Y_1, Y_2)$$

$$\leq max_{p(x1,x2)} I(X_1; Y_1) - max_{p(x1,x2)} I(X_2, Y_2)$$

$$= max_{p(x1)} I(X_1; Y_1) + max_{p(x2)} I(X_2; Y_2)$$

$$C \leq C_1 + C_2$$

4.3 Information Loss

Information loss *(L)* between two different sensors network models is calculated from conditional entropy of input and output data [5].

$$L(X \longrightarrow Y) = H(X|Y)$$

$$H(X|Y) = \sum_y P_Y(y) \ \left[-\sum_x P_{X|Y}(x|y)\log(P_{X|Y}(x|y))\right] \quad (4.3.1)$$

Similarly,

$$H(Y|X) = \sum_{x_i \in X} p(x_i)\, H(Y|X = x)$$

$$= \sum_{x_i \in X} p(x_i)\, H(p) = H(p) \quad (4.3.2)$$

Similarly, to calculate the information loss in between the cascaded channel system, we individually estimate the conditional entropy for each channel communication.

Intuitively, in cascaded channel, output Y of input data X is directly used as input to transmit to Z .This gave us:

$$L(X \rightarrow Z) \geq L(X \rightarrow Y) + L(Y \rightarrow Z) \quad (4.3.2)$$

4.4 Mutual Information over Cross correlation

Mutual information is an ideal metric for our sensor placement problem in multi-hop because it results in minimizing the conditional entropy of our object state. In long range underwater communication, placement of multiple sensors in hop increases the mutual information among transmitter and receiver reducing bit error rate, information loss, and large propagation delay.

Mutual information identifies and quantitatively characterizes relationship between data sets that are not detected by commonly used linear measures of correlation. Given two data sets as input and output of channel, $\{X\}=\{x1, x2, \ldots..xN\}$ and $\{Y\} =\{y1, y2, \ldots.. yN\}$, their mutual information, $I(X,Y)$, is the average number of bits of $\{X\}$ that can be predicted by measuring $\{Y\}$. Mutual information relationship is symmetrical, $I(X, Y) = I(Y, X)$. Analyzing observational data, calculation of the mutual information occurs in two contexts:

i) Identification of nonlinear correlation,

ii) In the investigation of causal relationships with directed mutual information.

Calculation of mutual information is important in the characterization of causal relationships between two information data set. Mutual information captures complex association between variables that are missed by standard correlation measures. By definition, a correlation measures, either linear or nonlinear, quantifies the degree of correlation between $\{X\}$ and $\{Y\}$ under their respective definitions, but it does not necessarily identify causal relationships in the sense of identifying which variable drives the other, if indeed such a relationship exists. However, the principle of the mutual information maximization follows naturally from the expected uncertainty minimization criterion in a Bayesian filtering framework [22].

4.5 Conclusion

In this chapter, information theoretic tools like entropy, channel capacity, mutual information, joint entropy, and conditional entropy are discussed. We relate our sensor network mode of multi-hop with respect to information theory knowledge and also mention why we choose mutual information over correlation to study the performance of network model.

Chapter 5

Modulation Techniques

In this chapter, we discuss some of the modulation techniques that will give a better performance and optimum information receiving techniques for underwater acoustic communications. In this thesis, we study two different types of modulation and use them in data communication process. PPM is the first one. This modulation technique is used by the vendor (Desert Star Systems). The basic idea of PPM is that the position of each pulse in relation to the position of a recurrent reference pulse is varied by each instantaneous sampled value of the modulating wave. In our experiment, we use m-sequence modulation and Binary Phase Shift Keying (BPSK) modulation, so we focus on these two.

5.1 PN-sequence modulation

Maximal length sequences are generated by using linear feedback shift register. In [12] it shows that shift registers result a binary output that is periodic with period, $N = 2^n - 1$, where n is the degree of a polynomial. For n –stage shift register, the total number of non-zero states will be $2^n - 1$ all having period of, $N = 2^n - 1$ .Shift registers sequence having maximum possible period for a n –stage are called maximal-length sequences or m- sequences. Maximum length sequences are very useful in spread spectrum technology because of following properties:

1. A maximal length sequence contains one more one than zero. The number of ones in the sequence is $\frac{1}{2}\ (N + 1)$.
2. The modulo-2 sum of an m-sequences and any phase shift of the same sequences is another phase of the same m-sequence (shift-and -add property)
3. If a window of width r is slid along the sequence for N-shifts each r-tuple except the all zero r-tuple will appear exactly once.

The periodic autocorrelation function is mathematically expressed as:

$$\theta_b(k) = \begin{cases} 1 & for\ k = lN \\ -\frac{1}{N} & for\ k \neq lN \end{cases} \tag{5.1.1}$$

where, l is any integer and N is the sequence period.

In our thesis, we generate the PN-sequence for the code length of 1024 by choosing the 10th order polynomial.

5.2 Direct Sequence Spread Spectrum (DSSS)/ Binary Phase Shift Keying (BPSK)

The DSSS process is performed by multiplying a carrier frequency and a pseudo-noise (PN) digital signal. The PN code is modulated onto an information signal using modulation techniques binary phase-shift keying (BPSK). For a DSSS system, the spreading rate is increased with higher number of chips per data symbol, which will lead to an improvement of the SNR per symbol in additive white Gaussian noise (AWGN). For time-varying channels, the gain depends on the stability of the channels environment that wave propagates in. The gain of the receiver is reduced if the channel changes considerably during one symbol period. This results in a net loss when the length of the spreading code is increased past a certain point.

Comparison of DSSS and FHSS based on performance depends on the characteristics of an acoustic channel. According to simulation done in [10], the primary limitation is the time variability. The DSSS performs very well when coupled with a chip rate equalizer. The variation in the channel gives the limitation on the performance of the receiver at high spreading rates. The FHSS is more vulnerable to the Doppler shift effect because the signals are transmitted in narrow bands, but more robust to multiple access interference (MAI) than DSSS. FHSS has a higher bit error rate than DSSS, though FHSS has simple receivers and gives robustness to the near-far problem especially when used with convolution coding and soft-decision Viterbi decoding, thus simplifying the power control functionality. However, performance for FHSS is limited in frequency-selective channels.

In DSSS the received signal is multiplied with the original pseudo noise code and integrated over the period on the data symbol, also known as de-spreading. The de-spreading will de-

correlate the multiple access interference made by multiple signals. The problem with this method is that it has a very high complexity and can be a problem to implement in small sensor with limited power [3].

Even though there are advantageous and disadvantageous for both direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS) the DSSS has the best performance in underwater acoustic communication. Therefore DSSS is chosen as the spread spectrum technique for the simulation in this study.

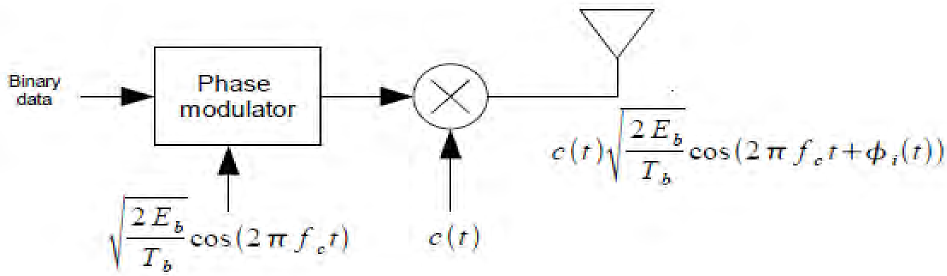

Figure 9. BPSK Transmitting channel model

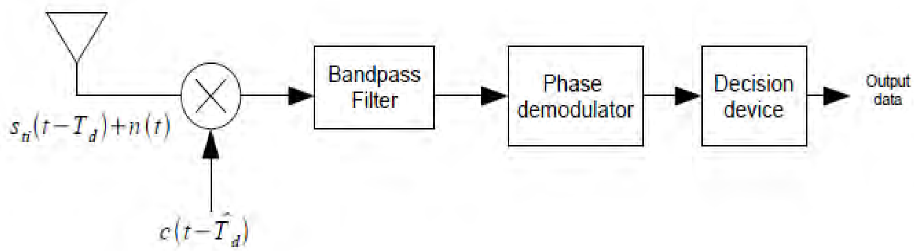

Figure 10. BPSK Receiving channel model

The advantages of direct sequence spread spectrum (DSSS) mentioned above are good arguments for using DSSS in underwater acoustic communication. In addition, its performance in simulations is also quite good and with some optimization the results can be better. The challenge in DSSS is to have good time synchronization between the transmitted code spreader and the received code de-spreader. To reduce the problem of noise, better filters can be used in the receiver. The disadvantage with using spreading codes is that the bandwidth is increased and this can be a problem in band-limited situations. To deal with multiple users and noise, the DSSS is used with Gold codes as spreading codes. These spreading codes work for detecting the correct symbols.

Chapter 6

Simulation and Analysis Study

In this chapter, we present an analytical and simulated result of systems channel capacity and function of proposed multi-hop sensor network in long range communication. We study the mathematical algorithmic result of transmission model, capacity bound and optimum frequency for link distance. Since we aim to maximize the throughput capacity of our sensor network by the placement of multi-hop sensor nodes, in the following, we describe the system capacity, transmission data rate, and an optimal distance.

Let X is the total number of bits of a packet. Let T_i represent the packet transmission time of a sensor multi-hop. By the law of large numbers, the throughput capacity of the network is [8]:

$$C = \lim_{n\to\infty} \frac{nX}{\sum_{i=1}^{n} T_i} = \frac{X}{E[T_i]} \tag{6.1.1}$$

We assume the length of data packet, X, is fixed; therefore in order to maximize the throughput capacity of the network, $E[T_i]$ needs to be minimized. Thus, the design objective of our system is to minimize the expected time that a node needs to transmit a packet to following node which we call it the expected packet transmission time. The packet transmission time is inversely proportional to the communication rate between transmitter and receiver. Since an underwater acoustic channel is time variant and different random network parameters such as the distance between the transmitter and receiver and channel noise affect the reliable communication rate, the packet transmission time is random. So the transmission model is based on the Shannon capacity bound for a point to point Gaussian channel.

We assume that the noise variance, N_o, is the same anywhere in the network. Let the signal power received by a receiver be P and the available bandwidth be BW. The channel capacity is:

$$C = BW \log_2\left(1 + \frac{P}{BW N_o}\right) bps \tag{6.1.2}$$

If the transmitter reference power is P, while the distance between the transmitter and receiver is l, by using (2), the bit rate between this transmitter and receiver is:

$$C = BW \log_2\left(1 + \frac{P}{l^{\alpha} N_o}\right) \; bps \tag{6.1.3}$$

where α is the positive constant representing path loss.

Similarly, if the transmitter has M bits to transmit to the receiver, the data transmission time is:

$$T(l,P,X) = \frac{M}{BW \log_2\left(1 + \frac{P}{l^{\alpha} N_o}\right)} seconds \tag{6.1.4}$$

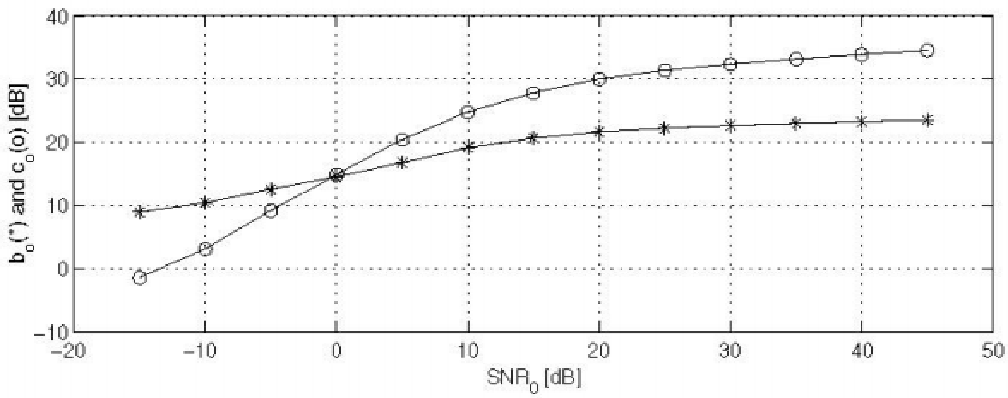

Figure 11. Target SNR v/s Capacity maximization: bandwidth and capacity scaling factor b_o and C_o

As it can be seen in Figure 9, the targeted SNR_o for communication between each single hop has direct dependence on scaling factor of bandwidth and capacity of the channel. From equation 2.2.1, the SNR for total link is characterized by parameter bandwidth, capacity and number of hops. For multi-hop relay setup of sensors in underwater, the overall link capacity and SNR affects in optimum selection of bandwidth and capacity calculation of each hop.

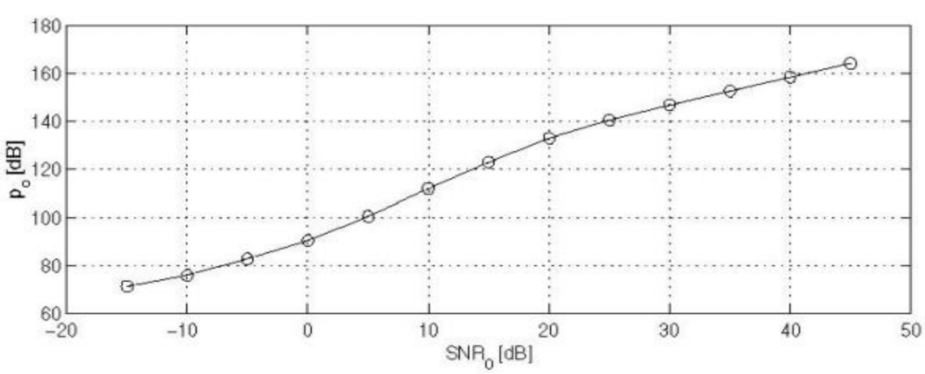

Figure 12. Target SNR under the Capacity maximizing definition: power scaling factor P_o

Figure 10 illustrates the transmission power parameter as a function of SNR. The results indicate that power scaling factor and power exponent exhibit some SNR dependence that increases the signal power and increases the performance of acoustic channel.

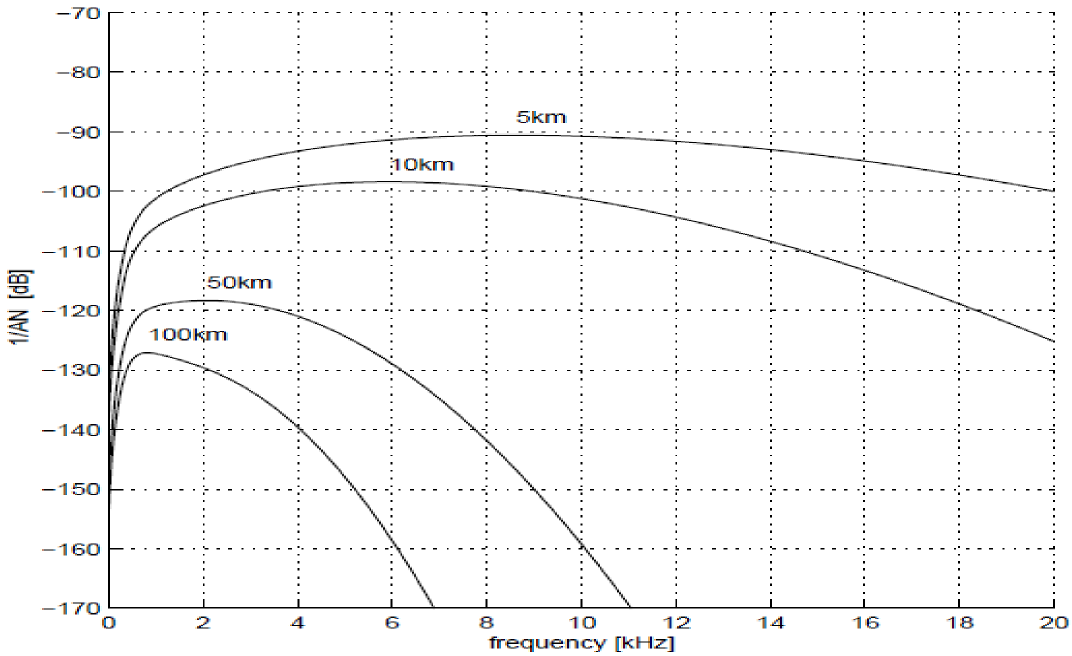

Figure 13. Relative SNR in an acoustic channel v/s frequency as a function of link distance

Figure 11 illustrates that for each transmission distance *l*, there clearly exists an optimal frequency *f* for which the maximal narrow-band SNR is obtained. Using the attenuation *A(l, f)* and the noise PSD, once can evaluate the SNR observed over a distance *l*. In our simulation result, we define 3 dB bandwidth at the various range of communication for *SNR(l, f)*.

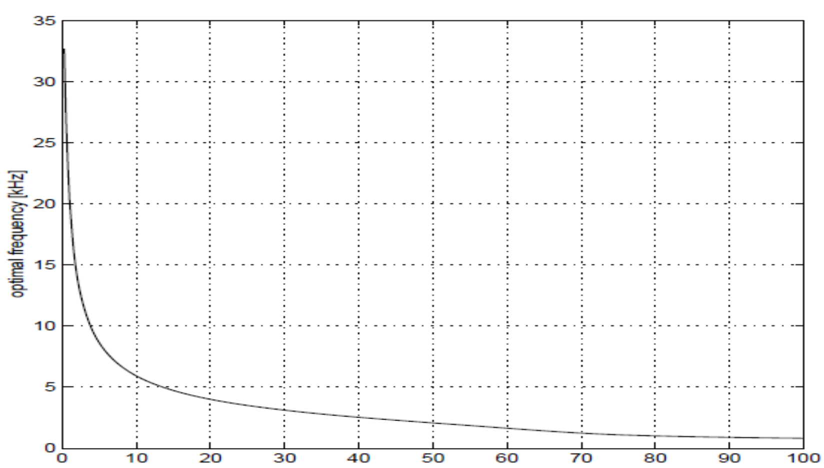

Figure 14. Optimal frequency *f*(*l*) with respect to link distance *d*

Figure 12 represents the optimal frequency plotted as a function of transmission distance. In practice, one may choose some transmission bandwidth around *f(l)* and adjust the transmission power so as to achieve desired SNR level.

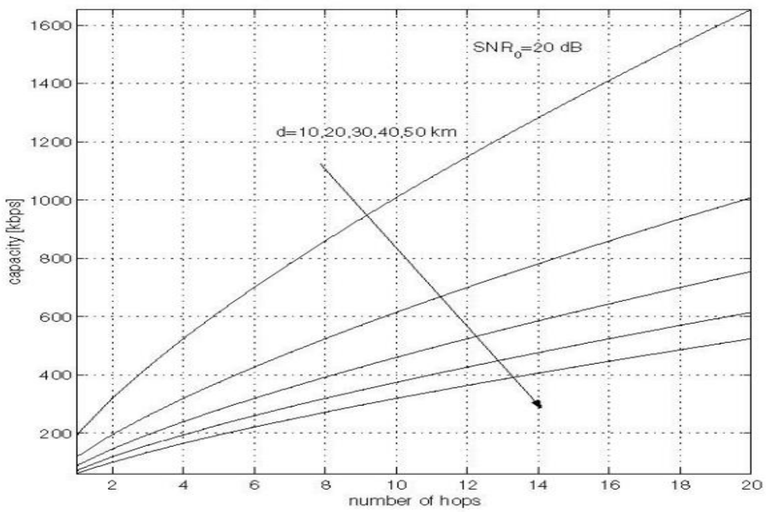

Figure 15. Capacity of Relay link v/s number of hops, *N* for varying link distance *d*

In figure 13, the capacity of multi-hop relay link is demonstrated with respect to number of hops. The capacity $C_N(d)$ versus the number of hops N is shown for varying link distance d. We observe that the capacity increases with the number of hops for a given link distance. As expected the capacity is lower for a greater link distance. This tells, number of hops should be in consideration for given link distance to find upper bound in mutual information between transmitted data and received data.

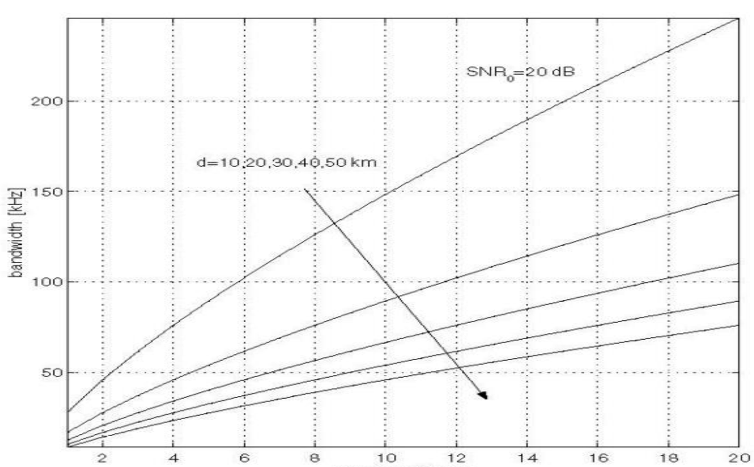

Figure 16. Bandwidth of Relay channel v/s number of hops, *N* for varying link distance

Figure 14 shows the similar trend like in capacity versus number of hops. The bandwidth availability for acoustic channel becomes more with decrease in communicating distance. The deployment of multiple sensors to form multi-hop relay network for given link distance gives an opportunity to use wide bandwidth for maximum data rate transfer.

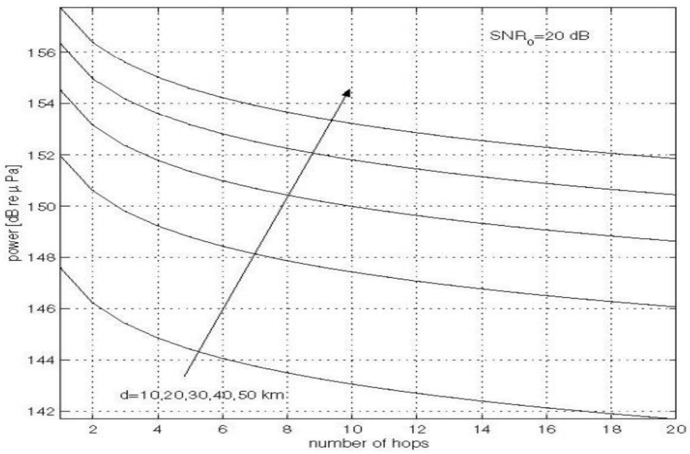

Figure 17. Total Transmission Power Vs. the number of hops, N

Figure 15 represents the relation between transmit power and number of hops for given link distance. As it can be expected, less power is required for a greater number of relays. Therefore, in underwater acoustic channel, number of relays shows heavy dependence on the capacity of channel.

Chapter 7

Experimental Set Up and Results

After a preliminary research and signal analysis, we concentrate our study to the main objective of our thesis; an experimental approach for placement of sensors in underwater for minimum BER and maximum mutual information. Our experimental model consisted of an indoor swimming pool, two pairs of SAM-1 acoustic transducers provided by Desert Star Systems, two portable computers both equipped with MATLAB software, signal processing toolbox, communication toolbox, a hydrophone to measure sound underwater, and an acoustic speaker to generate noise. The data is transferred using transducers and is processed in Matlab.

In our experiment, the transmitted signal has a carrier frequency of 17 kHz and the sampling rate of 8000. From the Figure 17, we can see that the power of noise is high for frequency range of 0 to 5 kHz. As the frequency increases we can observe that the power of noise is less than 38dB. So if we are able to transmit the signal in the frequency range where the noise power is relatively less, we can obtain better performance. Therefore, we choose 17 kHz of carrier frequency for our experiments.

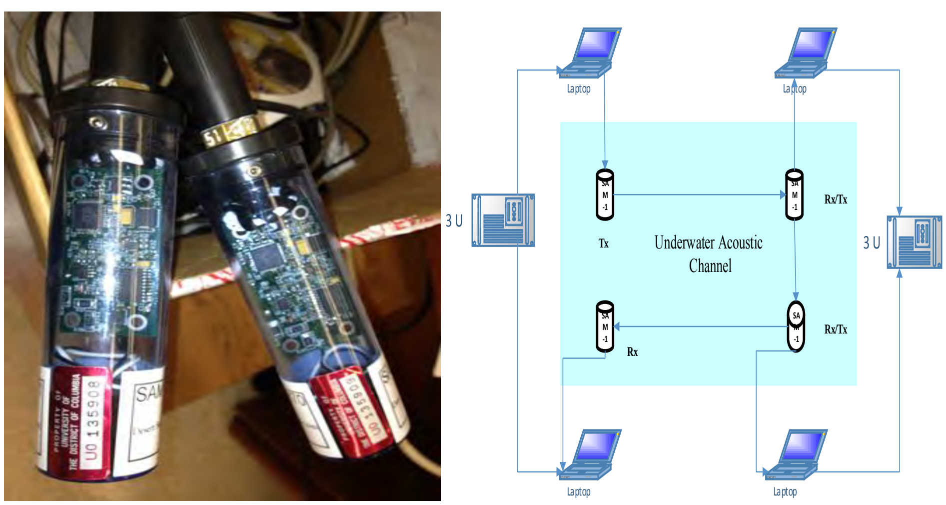

Figure 18. Acoustic Sensors by Vendor and Experimental set up in Underwater Communications

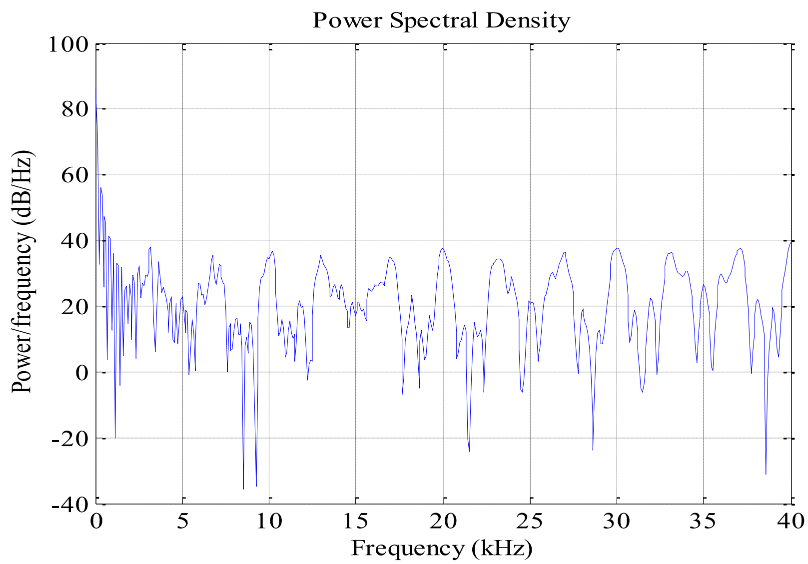

Figure 19. PSD of Noise *($N_o(f)$)* experimentally measured in underwater

Figure 17 shows that power of noise is high for frequency range of 0 to 5 kHz. As the frequency increases we observe that the power of noise decreases up to -12 dB. Therefore, we choose to transmit the signal in the frequency range where the noise power is relatively less, and gives better performance in terms of BER and mutual information bound.

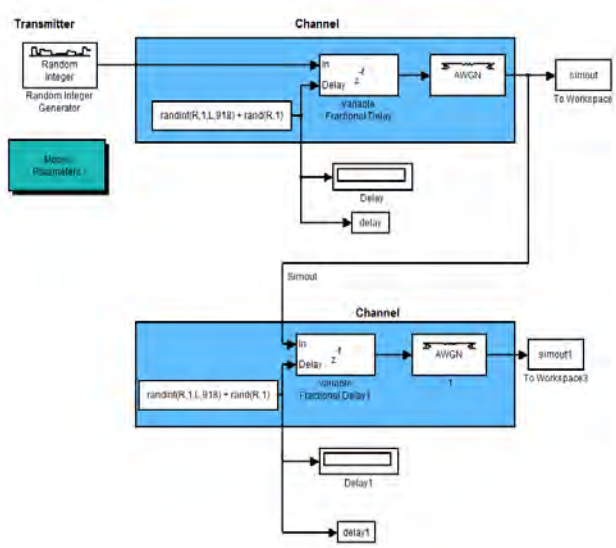

Figure 20. Matlab simulation Set Up for multi-hop network sensor model

Figure 18 gives the insight of how the multi-hop relay network is setup. In Matlab simulation, we connect an output from first hop to second hop as an input and transmit data with some delay and noise. Before transmitting a data to second hop, BER and mutual information is calculated and

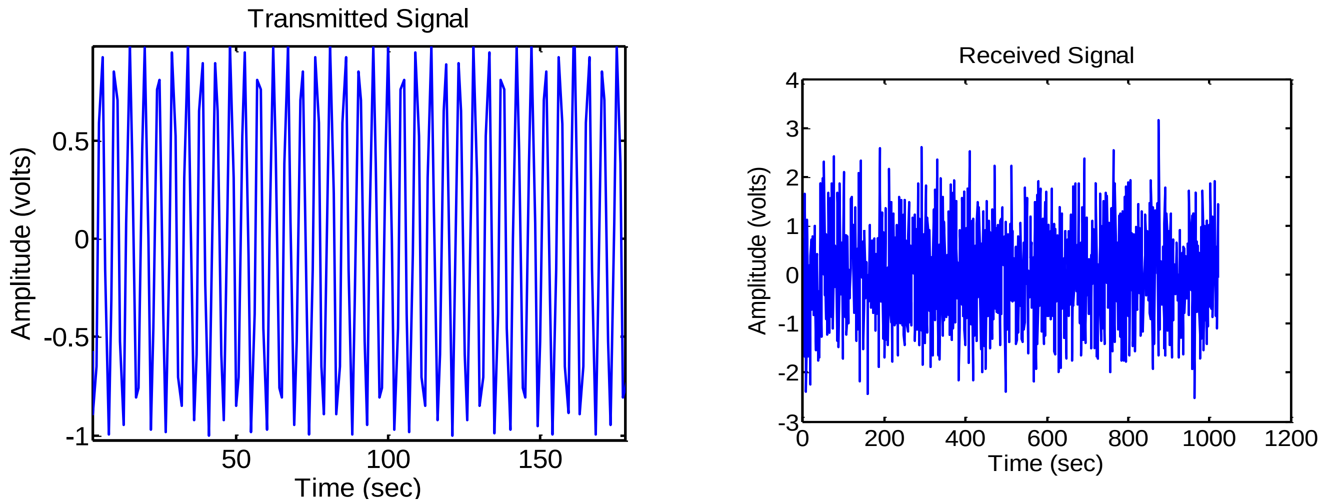

Figure 21 Transmitted and Received Modulated m-Sequence Signals (17 kHz)

data are regenerated such that noise and error does not get accumulated throughout the transmission.

Table 2. Modem Specifics and Operating Function

Type of command /specification	Operating function/condition of sensors
###	Sets to a command mode for configuration.
We used S5 for transmission @ 13bits /sec	Set acoustic transmit data speed
We used R5 for receiving @13bits/sec	Set acoustic receive data speed
Serial buffer	32 byte
Operating temperature	0-70 ^{0}C
Filter type	4th order band pass filter
Operating frequency for single channel receiver	33.8khz
Operating frequency of modem	33khz-42khz Omnidirectional
Sonar Data format	16- bit data + 4 bit checksum per word
Modulation	Pulse Position Modulation

In our thesis, we perform a serial data communication via serial port using RS-232 levels. The data are transmitted at 4800 baud and 8 data bits. To perform serial communication from Matlab software, we first define the serial port object and then configure device parameters for communication. Values sent, received, transfer status and bytes available are recorded in Matlab

for tracking purpose. We increase the buffer size of Matlab software to 1023 bytes (by default it is 512 byte).The received data is then loaded to workspace. We do the similar experiment using Simulink and record the data to the workspace.

Since there are only four stationary nodes in our network, we use a static routing table that lists the routing paths for all possible source-destination pairs. For example, we place the four nodes on a straight line, and label them as A, B, C and D respectively. If node A generates a message with the source field as A and the destination field as D, then the next-hop is node B and then node C in the routing table for the (A, D) source-destination pair.

Table 3. Bit loss test for different distance of sensors

Distance between sensors	No. of bits transmitted	Received no. of bits	Bit loss	Bit error rate
5 m	1023	1015	8	0.007
7 m	1023	1011	12	0.011
10 m	1023	1011	12	0.011

In Table 4, we transmit 1023 bits of binary sequences data to the receiver sensor node at a distance of 5 m. This channel transmits all 1023 bits; however it has bit error of 8 bits in average.

Table 4. Result analysis for First Hop Tx_1 and Rx_1 (d=5 m)

Bits transmitted	Bits received	BER	$I(X;Y)$	Information loss $H(X\|Y)$
1023	1023	0.0078	1.00	0.0
1023	1023	0.0087	1.00	0.00
1023	1023	0.0078	1.00	0.00

In Table 5, the transmitting data are exactly the received data from first senor node; however we filter the error bits that are incurred in first channel. This channel is also set for distance of 5 m between transmitter and receiver. We get a full communication of data between sensor nodes with bit error of 7 -8 bits in average.

Table 5. Result analysis for Second Hop Tx_2 and Rx_2 (d=5 m)

Bits transmitted	Bits received	BER	*I(X;Y)*	Information loss *H(X|Y)*
1015	1015	0.0068	1	0
1014	1014	0.0078	1	0
1015	1015	0.0088	1	0

In Table 6, we load the received data from sensor node 3 and transmit exactly to another sensor node in a relay network. This receiver is again at a distance of 5 m. The channel has full communication of data with bit error of approximately 7-8 bits.

Table 6. Result analysis for third Hop Tx_3 and Rx_3 (d=5 m)

Bits transmitted	Bits received	BER	*I(X;Y)*	Information loss *H(X|Y)*
1008	1008	0.0079	1	0
1007	1007	0.0079	1	0
1006	1006	0.0089	1	0

Table 7 shows our improvement regarding minimization in bit loss and bit error compare to direct transmission between two senor nodes and a relay network. The channel distance is approximately 15 m. The output result shows that the channel has bit error along with bit loss. This proves that transmission loss in underwater acoustic communication depends on distance.

Table 7. Result analysis for Tx_1 and Rx_4 (d=15 m)

Bits transmitted	Bits received	BER	*I(X;Y)*	Information loss *H(X|Y)*
1023	1012	0.0185	0.9156	0.0844
1023	1015	0.0156	0.9419	0.0581
1023	1009	0.0215	0.8952	0.1048

Table 8 shows that underwater acoustic communication (UAC) capacity is strongly dependent on transmission distance. Using more than one sensor as multi-hop network system

model, increases the mutual information and rate of data transmission with minimum bit error probability.

Table 8. Result analysis for Multihop relay link and direct link

S.N	Case study	*I(X:Y)*	BER	Information loss *H(X|Y)*
1	Tx_1 and Rx_1	1	0.0081	0
2	Tx_2 and Rx_2	1	0.0078	0
3	Tx_3 and Rx_3	1	0.0082	0
4	Tx_1 and Rx_4	0.9054	0.1853	0.0824

Conclusion and Future Work

The problem of an optimum placement of sensors in a multi-hop relay structure for long range acoustic communication in underwater channel have been investigated to maximize the mutual information and channel capacity. The optimum communication frequencies for given link distance and bandwidth available have been calculated where noise power is low. The deployment of sensors in multi-hop relay structure for large transmission range has been considered to minimize bit error rate and information loss as well.

Additionally, an analytical and experimental result of multi-hop sensor network model in a relay has been investigated to optimize the mutual information and maximize rate of data communication. It was advantageous to accomplish such transmission using relays since the available acoustic bandwidth decayed with increase in distance. Moreover, numerous applications required a relay acoustic link where data transmission had to be accomplished beyond short distances. The multi-hop relay structured that we have used would be suitable fit to address the issues of power and energy consumption, and link delay along with maximizing mutual information.

The improvement in mutual information and data rate transmission has been investigated using information theoretic tools such as entropy, conditional entropy, and information loss between transmitted and received data signals. Based on our experiment and simulation result, we concluded that the mutual information between transmitted and received data signal can be maximized by placing extra sensor nodes in between a transmission range which also decreased BER and information loss. The problem occurred in our analytical result was an additional delay due to relay link. However, we observed that delay depended on the rate at which the information is transmitted as well. This fact implied an interesting property of an acoustic link: although each relay introduces an additional delay, as the hops become shorter transmission can be accomplished faster over each hop. This improvement is specific to the underwater acoustic environment, where bounds of mutual information and bandwidth are dependent on the transmission distance.

During our experiment we had several issues with data compatibility with the software. It took several hours to run the Matlab programs. Memory buffer size of sensors was another issue, which only transmit real data signal through serial communication. We also observed that Matlab

serial communication does not support complex signals. We had problems with the sensors since they transmitted some random signals by themselves due to unknown internal error.

We can expand our work for movable sensor nodes in underwater channel to address the issues with Doppler spread. Along with a relay network, we can address a multi-path channel model and use the wireless communications knowledge of MRC (Maximal Ratio Combination) to increase the detection quality of received signal.

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Appendix

MATLAB SIMULATION CODE FOR BPSK TRANSMISSION OVER AWGN CHANNEL

```
close all;
clear all;
clc;
SNRdB=1:1:12;                          %Signal to Noise Ratio in dB
SNR=10. ^(SNRdB/10);                   %Signal to Noise Ratio in Linear Scale
Bit_Length=10^6;                                %No. of Bits Transmitted
BER_Simulated=zeros(1,length(SNRdB));           %Simulated Bit Error Rate

%Detection Scheme:(Soft Detection)
%+1 if o/p >=0
%-1 if o/p<0
%Error if input and output are of different signs

%% BPSK Transmission over AWGN channel
      parfor  k=1:length(SNR);
              x=(2*floor(2*rand(1,Bit_Length)))-1;
              y=(sqrt(SNR(k))*x)+randn(1,Bit_Length);

        BER_Simulated(k)=length(find((y.*x)<0));%Total number of bits in
error
      end
      BER_Simulated=BER_Simulated/Bit_Length;
      semilogy(SNRdB,BER_Simulated,'m-<', 'linewidth' ,2.0);
      hold on
      semilogy(SNRdB,qfunc(sqrt(SNR)),'b-','linewidth',2.0);
            %Theoritical Bit Error Rate
      title('BPSK over AWGN Simulation');xlabel('SNR in dB');ylabel('BER');
      legend('BER(Simulated)','BER(Theoritical)')
      axis tight
      grid
```

INFORMATION THEORETIC TOOLS TO DETERMINE MUTUAL INFORMATION, INFORMATION LOSS AND BER

```
%**********Events Probability Distribution**********
%Event A--> P(x=1, y=1); Event B--> P(x=0, y=0);
%Event C--> P(x=1,y=0) ; Event D--> P(x=0, y=1);
%Event F--> P(Y! =0, 1) No Joint Probability ;( Bit Loss)

      A=0; B=0; C=0; D=0; F=0;     % Events Initialization
      n=1023;                      %Number of transmitted bits

      %%Adjusting Data
      for i=1:n;
        x(i,:)=  (-1).^i;
      end;
      sx=size(x);
      sy=size(y);
      for i=sy:n
      y(i)=5;
      end;
```

```
      x(x==-1)=0; y(y==-1)=0;     %Switching(-1)-->(0); for simpler
      calculation
z=x-y;

for i=1:n
   if z(i)==0 && x(i)==1
        A=A+1
            elseif z(i)==0 && x(i)==0
              B=B+1
                elseif z(i)==1 && x(i)==1
                 C= C+1
                   elseif z(i)== -1 && x(i)==0
                     D=D+1
   else F= F+1
   end
   end
   Tot=(A+B+C+D+F);  %Sum of All Events

%Joint Probabilities
      PA= A/Tot;      %P(y=1,x=1);
      PB= B/Tot;      %P(y=0,x=0);
      PC= C/Tot;      %P(y=0,x=1);
      PD= D/Tot;      %P(y=1,x=0);
      PF= F/Tot;      %P(y!=1,0);

%since binary data;
      Px1=sum(x(x==1))/n; Px0=sum(x(x==0))/n;

% Estimating the P(y=1) and P(y=0);
      count1=0; count2=0; count3=0;
      for i=1:n
      if y(i)==1
              count1= count1+1;
            elseif y(i)== 0
                count2= count2+1;
           else count3=count3+1;
           end
      end
          Py1=count1/n;   % P(y=1)-->Probability of receiving 1;
          Py0=count2/n;   % P(y=0)-->Probability of receiving 0;
          Pyy=count3/n;   % P(y!=0,1)-->Probability of receiving null;

          % Conditional Probabilities
          Py1X1= PA/Px1;   %P(y=1|x=1)  = P(y=1, x=1)/P(x=1);
          Py0X0= PB/Px0;   %P(y=0|x=0)  = P(y=0, x=0)/P(x=0);
          Py0X1= PC/Px1;   %P(y=0|x=1)  = P(y=0, x=1)/P(x=1);
          Py1X0= PD/Px0;   %P(y=1|x=0)  = P(y=1, x=0)/P(x=0);

    % Entropy, Joint Entropy and Mutual information Calculation
          Hx= (n*Px1*log2 (1/Px1));       % H(x) Entropy(transmitted bits)

    % H(y) Entropy (Received bits);
          Hy= (Py1*log2(1/Py1))+(Py0*log2(1/Py0))+(Pyy*log2(1/Pyy));

    % H(x,y) JointProbablility
          Hxy= (-1*PA*log2 (PA))-(PB*log2 (PB))-(PC*log2 (PC))-(PD*log2(PD))-
         (PF*log2(PF));
```

```
        HxY=Hxy-Hy;      %Conditional Entropy H(x|y)=H(x,y)-H(x);
        HyX=Hxy-Hx;      %Conditional Entropy H(y|x)=H(x,y)-H(y);

        Ixy=Hx-HxY;      % I(x,y) Mutual Information between Transmitter and
    Receiver
```

BIT ERROR RATE SIMULATION

```
%Tx=Transmitted bits vector
%Rx=received bits vector
%LTx= length of transmitted bits vector
%LRx=length of received bits vector
Clear all;
%Partial cross-correlation from bit vector Tx and RX:
      for lag=1:length(Rx)-length(Tx)-1;
          corr(lag)=Tx.*Rx(lag:length(Tx)-1+lag)';
      end;

%correct bit offset.
      off= find(corr== max(corr))-1;

%error vectore err.
      err= Tx-Rx(off+1 : length(Tx)+off);

%Total number of bit errors.
      te= sum(abs(err));
%Calculate BER.
      ber= te./length(Tx);
```

PSD CODE FOR NOISE

```
Fs = 80000; % Sampling frequency
load('Simulink_Serial_3_2_2014NOISE.mat')
x = xcorr(Noise); %Noise is the measured noise data loaded form workspace
figure;plot(x);xlabel('Autocorrelation
Length');ylabel('Amplitude');title('Autocorrelatoin of Measured Noise')
nfft = 2^nextpow2(length(x));
Pxx = abs(fft(x,nfft)).^2/length(x)/Fs;
% Create a single-sided spectrum
Hpsd = dspdata.psd(Pxx(1:length(Pxx)/2),'Fs',Fs);
figure; plot(Hpsd);
```

DESERT STAR SYSTEM (VENDOR) SERIAL COMMUNICATION TRANSMISSION CODE

```
clc;
clear all;
%----SERIAL--COMMUNICATION--Transmission_ Code
% Find a serial port object.
s = instrfind('Type', 'serial', 'Port', 'COM6', 'Tag', '');
% Create the serial port object if it does not exist
% otherwise use the object that was found.

if isempty(s)
    s = serial('COM6');
     else
    fclose(s);
    s = s(1)
```

```
end
%configure instrument object, s
set(s,'InputBufferSize',100) % Serial Port will hold data until 1024 bytes
set(s,'BaudRate',4800);
set(s,'DataBits',8);
set(s, 'FlowControl', 'none');% software handshaking is  used to control data
flow
set(s,'Timeout',120.0);
%%
% Connect to instrument object,s
fopen(s);
%fprintf(s,'###')
%fprintf(s,'R5')
%fprintf(s,'D')
Session_1= fread(s);
% Disconnect AND Clean up all objects
fclose(s);
delete(s);
```

DESERT STAR SYSTEM (VENDOR) SERIAL COMMUNICATION RECEIVER CODE

```
% Find a serial port object.
s = instrfind('Type', 'serial', 'Port', 'COM4', 'Tag', '');
% Create the serial port object if it does not exist..
% ..otherwise use the object that was found.

if isempty(s)
    s = serial('COM4');
     else
    fclose(s);
    s = s(1);
end
%%
%configure instrument object,s
set(s,'OutputBufferSize',1024) % Serial Port will hold data until 1024 bytes
set(s,'BaudRate',4800);
set(s,'DataBits',8);
set(s,'Timeout',60.0);
set(s, 'FlowControl', 'software');% software handshaking is  used to control
data flow
%%
load TREX_M10_FB5K_2004116093249_CH3.mat
load trigsignal_M10_Fb5k.mat
load TRSEQsPLIT.mat

% Connect to instrument object,s
fopen(s)
fwrite(s,trseq12);
%pause(20.0);
%fwrite (s,trseq2);
%pause(20.0);
%fwrite (s,trseq3);
% Disconnect AND Clean up all objects
fclose(s);
delete(s);
```